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The article is a first attempt at elementary quantitative examination of the process of formation of advective fogs in the surface layer of the atmosphere.

On the basis of analysis of solutions of equations of turbulent diffusion of heat and moisture obtained for the conditions of the surface layer of the atmosphere, the conditions of formation of advective fogs according to the initial characteristics of the air and the underlying surface are investigated. Vapor fogs are examined at greater length. In this case it is shown that in addition to the initial characteristics (temperature, humidity) of air flowing over the surface of water, the chief characteristics determining the development of fog are the size of the body of water and the intensity of the turbulent moisture and heat exchange between the surface of the water and the moving air. Approximate results are obtained for conditions of natural dissipation of vapor fogs.

Fogs may arise in the surface layer of air when the air becomes saturated due to the temperature having fallen to the dew point or due to enrichment of the air with water vapor (for example, owing to evaporation from the underlying layer). For the formation of fog, in addition to a drop in air temperature to the dew point or an increase in humidity to the saturation point, there is necessary a certain additional drop in temperature and an additional introduction of moisture in order to create in the air sufficient water content to cause the reduced visibility associated with fog (visibility of less than one km).

With the presence of condensation nuclei in the air (which is practically always observed), the occurrence of fog is determined chiefly by a change in the temperature and humidity of the air. For the surface layer of air one of the principal processes causing the mentioned changes is the heat and moisture exchange between the air and the underlying surface. Under the influence of this heat and moisture exchange fogs also occur in the surface layer of air, especially the so-called advective fogs.

From the physical point of view such fogs may be divided into 2 groups.

(a) Fogs occurring due to a decrease in air temperature under the influence of heat exchange between the air and the colder underlying surface. With this the moisture content of the warm air moving over the cold underlying surface undergoes no substantial change. In this way the advective fogs of winter in our latitudes are formed. The densest advective fogs of this type are formed in the case of a movement of warm humid air over the cold underlying surface.

(b) Fogs occurring due to a change in the temperature of the air and a substantial change in its moisture content. A characteristic example of such fogs is the so-called vapor fog (sometimes called steam fog). Vapor fog arises with the movement of air over a surface from which intensive evaporation occurs, causing a considerable increase in the humidity of the air. In this case the air flowing over the surface must have a lower temperature than the surface. At an inverse relation of temperature the process of evaporation, increasing the moisture content of the air, cannot lead to the formation of fog.

It must be pointed out that with considerable difference in the temperature of the moving air and that of the underlying surface, even under winter conditions evaporation may be quite considerable and capable of insuring saturation of the air with water vapor when the area of the underlying surface is relatively small. In the case under consideration, not only the humidity but also the temperature of the moving air undergo a change.

The most typical example of vapor fog is the fog observed in winter over unfrozen water surface.

Let us examine this case of fog formation in greater detail.

As has already been mentioned, for explanation of the conditions giving rise to vapor fogs it is necessary to examine the processes of heat and moisture exchange between moving air and the surface of the water.

Let us assume that air with a temperature and humidity of T_1 and q_1, respectively, moves over a water surface with a temperature of T_w. Designating the temperature and humidity of the air above the surface of the water as T and q, we have the equation for the values T and q:

$$u\frac{\partial T}{\partial x} = \frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z}\right], \qquad u\frac{\partial q}{\partial x} = \frac{\partial}{\partial z}\left[k\frac{\partial q}{\partial z}\right]. \qquad (1)$$

where u is the speed of the wind, coinciding in direction with the x axis, and k is the coefficient of turbulence.

Since we are investigating the simplest theory of this phenomenon, we shall use the simplest form of the equation for heat and moisture exchange.

Solution of equation (1) for the functions k and u was done in the work listed in item [1] of the reference literature and has the following form:

$$T = T_1 + (T_w - T_1)F\left(\frac{1}{L}, 2p\right), \qquad q = q_1 + (q_w - q_1)F\left(\frac{1}{L}, 2p\right). \qquad (2)$$

Here q_w is the saturation humidity corresponding to the temperature of the surface of the water.

The function of $F\left(\frac{1}{L}, 2p\right)$ is well known and well tabulated [2]. It describes the change in temperature and humidity of the air moving over the surface of the water.

Generally speaking F depends on 2 parameters; however, parameter p changes but little and may assumed equal to 0.1.

Parameter L is simply expressed through coordinates x and z:

$$[illegible] \qquad (3)$$

where K_1 and u_1 are the values of the coefficient of turbulence and wind velocity, respectively, at the elevation z_1.

We note that the function changes from zero (with $x = 0$ or $z \rightarrow \infty$) to unity (with $x \to \infty$ or $z = 0$). In the first case the temperature and humidity assume the initial values. The value of parameter L, on which the function F depends, is determined by the size of the body of water over which the air flows, the elevation above the surface of the water, and the ratio k_1/u_1.

Thus, the sole physical parameter determining the temperature and humidity of the moving air is the ratio k_1/u_1. Its value is well known for the equiponderant conditions over dry land and in the first approximation it may be adopted for calculations associated with vapor fogs. In addition, the elementary theory of air temperature and humidity changes presented here permits, with the use of relatively simple measurements, calculation of the value of k_1/u_1.

Actually, as formulas (2) and (3) show, in order to calculate the ratio k_1/u_1 it is necessary (in the direction of the wind) to measure the temperature or the humidity of the air at 2 points (for example, on the leeward and windward shores of the body of water) or at 2 points of an open surface of water. If the ratio k_1/u_1 is known, then it is easy to obtain the value of the function F for any values of x and z.

With F known we will attempt to explain the conditions of formation of fog. For simplicity of calculation we will assume at first that the values T_1 and q_1 (initial temperature and humidity of the air) do not change with elevation.

It is evident that fog may be formed under the condition

$$q > q_s, \tag{4}$$

where q_s is the saturation humidity for the given temperature. The condition in (4) may be rewritten as

$$q = q_s + \delta, \tag{5}$$

where δ is a certain additional amount of condensed moisture causing the decrease in visibility which is characteristic of fog. The quantity δ equals the aqueousness of the fog and its value may now be easily determined.

If use is made of the known dependence of q_s on the temperature and the relations in (2), then condition (5) for formation of fog is given in greater detail in the following form:

$$r_1(1-F) = \exp\left(\frac{a(T_w - T_1)F}{b+T_1}\right) - F\exp\left(\frac{a(T_w - T_1)}{b+T_1}\right) + \frac{\delta}{q_0}\exp\left(-\frac{aT_1}{b+T_1}\right), \tag{6}$$

where r_1 is the initial relative humidity of the air, a and b are the constants of the Magnus formula, and q_0 is the saturation humidity at 0°C.

The meaning of relationship (6) is as follows. If air with a relative humidity of r_1 and a temperature of T_1 flows over a body of water with a surface temperature of T_w, then above the surface of the water there is formed a fog with a density δ only on the condition that T_1, T_w, r_1, and δ with the given value of F satisfy equation (6).

To simplify further analysis we shall assume that $T_w = 0^\circ$C. In other words, we shall examine the case of formation of winter vapor fogs above unfrozen water with a surface temperature of 0°C.

It must be pointed out that such conditions are observed in nature, and hence the case under consideration is real. It is not possible here to shed further light on the sort of natural processes under which the assumed condition of $T_w = 0^\circ$ C is obtained.

On the basis of equation (6), with $\delta/q_0 = 0.02$ (which corresponds to a fog water content of 0.1 g/m^3) it is possible to calculate the necessary air temperature (designated in Figure 1 as T_k) in order that, with a given relative humidity r_1 and a given value of function F, fog may be observed.

The results of the calculation are depicted graphically in Figure 1, with values of T_k and F marked off along the axes. The 3 lines plotted in the figure correspond to initial values of humidity of 70, 90, and 100%. The curves show that in the formation of fog, in addition to the determined values of the initial characteristics of the air (T_1 and r_1), the size of the body of water and the intensity of the heat and moisture exchange between the air and the surface of the water are also of considerable importance. The role of the initial humidity is seen from the following example. If $F = 0.2$, then for $r_1 = 70$, 90, and 100%, the initial temperature of the air (counting from 0°) must correspondingly be -19, -14, and -9°.

The influence of the size of the body of water and of the intensity of the heat and moisture exchange (that is, of the value of function F) is easily illustrated by the following example.

If $r_1 = 90\%$ then the values of T_k, in dependence on F, may vary from -10 to -24°.

It is clear that similar curves may be plotted for any values of fog water content (that is, for fogs of various density. For determination of the function F we plot its curve according to values of the parameter L. The value of the latter is obtained from formula (3). For conversion to the quantities x and z the value of the ratio $k_1/u_1 = 0.015$ m. This value is determined for equiponderant conditions in the air and for average roughness of the surface.

We will briefly examine the first of the abovementioned types of fog. While it does not belong to the vapor fogs, its physical description is much like that of the latter. In this case, as was noted above, the moisture content of the moving air undergoes no appreciable change, whereas the temperature changes considerably, which is the determining factor in the formation of the fog.

As in the preceding discussion, the conditions of fog formation may be written in the following form:

$$r_1 = \exp\left(-\frac{[illegible](T_w - T_1)F}{[illegible] + T_1}\right) + \frac{\delta}{q_0} [illegible] \left([illegible] - \frac{aT_1}{b + T_1}\right). \qquad (7)$$

Analysis of this formula shows that for the most characteristic value of function F the formation of fog is possible only with an initial humidity r_1 not less than [illegible]%. The characteristic value of function F may be taken at 0.5, since [illegible] shows that with F greater than 0.5 the temperature and humidity change [illegible] slowly.

It is interesting to note that with the given value for $T_w - T_1$ and with the humidity r_1 equal to 50 or 70%, from equation (7) we obtain values for the initial temperature of fog formation with a given density (in the

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calculation [illegible] have assumed $\delta/q_0 = 0.1, 0.05$) correspondingly equal to 70 or 50%. [illegible] shows that with given initial humidity the formation of [illegible] considerable differences in temperature ($T_w - T_1$ [illegible] -10°), is practically impossible. On the other hand, with $r_1 = 90$, [illegible] the formation of fog is possible with an air temperature from 3 to [illegible]. Thus, the occurrence of advective fogs in winter, when moist air [illegible] over a colder underlying surface, is easily explained.

The [illegible] theory, as has been mentioned, is an extreme simplification of the process of fog formation. However, the following circumstances must be kept in mind. Certain of the assumptions in developing the theory here are not fundamental. In particular, the theory is easily generalized in the case of initial temperature and humidity and the variables q_w and T_w varying with elevation. Owing to lack of space, we will not derive these results here. It would scarcely be expedient to examine more complex conditions at the surface (for example, the heat-balance equation), since this, in addition to complicating the task, requires the introduction of physical parameters (for example, the heat characteristics of snow, soil, etc) about which little is known at present, whereas the values T_w and q_w for many cases are easily measured.

In addition, certain factors accompanying the formation of fog have not been taken into consideration, though they are easily evaluated. In particular, with the condensation of water vapor, as is known, the air temperature will change somewhat. This change may be approximately calculated in the following manner. If the temperature due to condensation is designated by ΔT_v, then on the basis of the foregoing we obtain

$$\Delta T_v = \frac{L}{C_p}(q - q_s) \qquad (8)$$

Here L is the heat of evaporation, C_p is the heat capacity of the air.

Using the known formula for q_s and formula (2), we may calculate the value ΔT_v. The calculations show that under ordinary conditions the value ΔT_v is approximately 50-100 times less than the value ΔT as determined from formula (2) (that is, the change in air temperature as a result of heat transformation is many times less than the change of this value under the influence of condensation of water vapor in forming the surface fog. Hence, the effect of the change in air temperature under the influence of condensation of water vapor apparently plays an insignificant role.

It is also of interest to note that fogs caused by a reduction in air temperature, given approximately identical initial characteristics of the air (fogs of group a), possess a higher density than the fogs of group b.

The thermodynamic aspect of this phenomenon first attracted the attention of D. L. Laykhtman [3], who showed that in the occurrence of fog a reduction in air temperature plays a greater role than a change in humidity. The correctness of this statement can be shown in the light of the presented elementary theory.

Figure 3 shows the relative humidity of air as calculated for fog formation of types a and b. Notwithstanding the fact that the range of relative humidity may not be exhaustively presented in the characteristic curve of the process, the curve nevertheless clearly shows that in case a, the humidity r rises more sharply than in case b.

In many cases the actual process of fog formation may differ considerably from the [illegible] discussed here. In particular, in certain cases it is necessary to complicate the form of equation (1) due to consideration of certain factors (for example, a nonstationary process or horizontal diffusion).

Moreover, it is not always possible to use conditions of complete similarity in the processes of heat exchange and moisture exchange. However, these questions are beyond the scope of the present article and require special examination. Here we shall merely attempt to obtain certain basic results relating to the process of fog formation in the surface layer of air by means of an elementary physical investigation.

As Figure 3 shows, in the formation of fogs of type a the value r may reach a maximum value at a certain value of F. More detailed examination of this problem shows that the law of change of r, shown in Figure 3, is typical. This change of r in the function F apparently has the following physical meaning. With the movement of air over a warm underlying surface the air becomes warmed and laden with water vapor. The latter, causing (under certain conditions) an increase in relative humidity, gives rise to the formation of fog. However, with further movement of the air the relative humidity, upon reaching a certain maximum, may again decrease. This circumstance points to a possible natural dissipation of vapor fog. In fact, in nature, as is known, vapor fogs are observed only in the littoral zone or regions of marked temperature contrasts (for example, in the case of marine currents). This is explained by the fact that the initially formed fog dissipates as a result of heating of the air mass. Hence it is of interest to explain under what conditions natural dissipation of fog of type b is possible.

In the first approximation it may be assumed that the fog may be dissipated only in the event of a decrease in r. Hence values of the functions F_k at which dissipation of the fog is possible may be determined approximately from the condition

$$\frac{\partial r}{\partial F} = 0.$$

Hence we obtain the following form for determining F_k:

$$F_k = \frac{r_1[(b+T_1)+a(T_w-T_1)]-(b+T_1)\exp\left[a\left(\frac{T_w}{b+T_w}-\frac{T_1}{b+T_1}\right)\right]}{a(T_w-T_1)\left\{r_1-\exp\left[a\left(\frac{T_w}{b+T_w}-\frac{T_1}{b+T_1}\right)\right]\right\}}. \qquad (9)$$

Formula (9) permits calculation of the values of F_k for various values of T_1, r_1, and T_w. In particular, with $T_w = 0^\circ$ and given values of $r_1 = 80$ and 100%, the values of F_k (as Figure 4 shows) vary from 0.3 to 0.5 (with T_1 lying within the range of -30 to -15 °C).

On the basis of Figure 2 we find that the value of parameter L is greater than 60. If we assume that $z = 1$ m and $k_1/u_1 = 0.015$, then dissipation of the fog proves possible with x greater than approximately 2 km (that is, the fog may be dissipated at a distance of approximately 2 km from the shore).

In conclusion I think it necessary to point out that cases of the formation of fogs of types a and b are examined in A. G. Amelin's well-known monograph [4]. However, A. G. Amelin deals chiefly with the thermodynamic aspect of the process, which may be conclusive for the formation of fog under laboratory or industrial conditions, but cannot to any extent be considered adequate for examination of this process under natural conditions.

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[Figures]

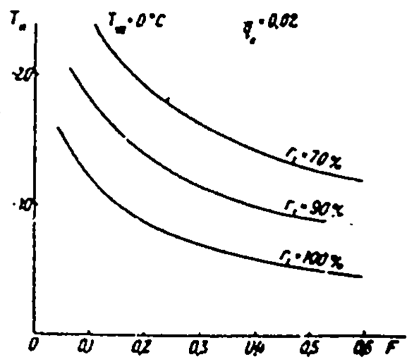

Figure 1

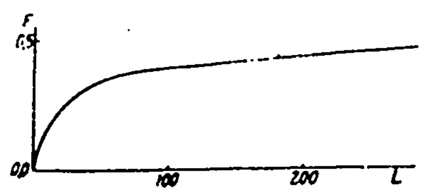

Figure 2

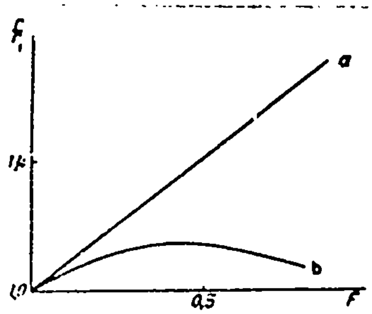

Figure 3

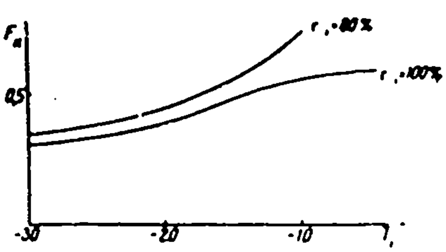

Figure 4

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